

ФИЗИКА АТМОСФЕРЫ И ГИДРОСФЕРЫ ATMOSPHERE AND HYDROSPHERE PHYSICS

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Features of small-scale artificial irregularities in the high latitude ionospheric F-region from remote sensing observations

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Abstract. Powerful HF radio waves interacting with the ionosphere accelerate or heat electrons, pushing the ionospheric plasma out of equilibrium and leading to the creation of various non-linear phenomena. One of the most prominent phenomena discovered from HF heating experiments is the generation of small-scale artificial field-aligned irregularities (AFAI). AFAI induce bi-static scattering of HF and VHF signals, providing their propagation in the frequency range and over distances unattainable in the natural ionosphere. This makes it possible to create HF-driven radio communication channels. We present results from an EISCAT/Heating (Tromsø, Norway) experiment on 18 February 2013, concerning the features and behaviors of AFAI in the high latitude ionospheric F-region induced by high power HF radio waves with O- and X-mode polarization using the bi-static scatter method. Joint use of various remote diagnostics tools, including the multichannel HF Doppler equipment, oblique sounding and the CUTLUSS backscatter radar provides a more comprehensive and complete AFAI study, including the size of the artificially disturbed region occupied with AFAI, the frequency band of bi-static scatter signals (BSS), the fine structure of BSS, the intensity, growth and decay times of AFAI. It has been found that O- and X-mode AFAI have different characteristics and generation mechanisms.

Keywords: high latitude ionosphere, remote sensing, artificial field-aligned irregularities, powerful HF radio wave, heating facility, bi-static radio scatter

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Introduction

The diagnostics and forecasting of phenomena occurring in near-Earth space and produced by solar-terrestrial connections is becoming an increasingly urgent task since automatic spacecraft operate there and astronauts work at manned space stations. In addition, the ionosphere is a medium that influences radio wave propagation, thereby affecting the performance of radio communication, navigation and telecommunications systems. One of the methods for studying the ionosphere is to radiate into it powerful HF radio waves using special high-power ground-based HF radio transmitters, so-called HF heating facilities. Powerful HF radio waves interacting with the ionosphere accelerate or heat electrons, pushing the ionospheric plasma out of equilibrium. Investigations of the artificially disturbed local region of the ionosphere that arises in this case are of considerable interest to scientists due to the possibility of studying the physical features of variations in ionospheric parameters that are not fully understood today compared with their observations in natural conditions. The interaction of high-power HF radio waves with the ionosphere leads to a variety of non-linear phenomena in the ionosphere that can be studied on a controlled and repeatable basis.

One of the most prominent phenomena discovered from HF heating experiments is the generation of small-scale artificial field-aligned irregularities (AFAI), which were profitably investigated at all HF heating facilities in the world [1–4]. AFAI induce bi-static scattering of short-wave and ultra-short-wave (HF and VHF) signals, providing their propagation in the frequency range and at ranges unattainable in the natural ionosphere. This makes it possible to create HF-driven radio communication channels.

The modification of the ionospheric F-region by powerful HF radio waves is commonly produced by using ordinary (O-mode) polarized radio waves. In this case, radio waves effectively interact with ionosphere plasma of F2 layer at altitudes between the upper hybrid resonance and the HF wave's reflection point. This leads to thermal parametric (resonance) instability excitation, which, in turn, leads to the generation of AFAI [2, 3].

It is well known that the ordinary mode of the HF radio wave reflects from the ionosphere at an altitude where the plasma frequency f_o is equal to the frequency of the HF radio wave f_H , $f_o^2 = f_H^2$.

The extraordinary (X-mode) HF radio wave reflects from the ionosphere at the point where the local plasma frequency is determined as $f_o^2 = f_H(f_H - f_{ce})$, where f_{ce} is the electron gyro frequency. Hence, the extraordinary mode wave reflection point is lower than the height of the upper hybrid resonance and the height of the ordinary wave reflection point. Accordingly, the extraordinary polarized (X-mode) high power HF radio wave is not able to cause AFAI generation via thermal parametric (resonance) instability.

However, the results of recent experiments at the EISCAT (European Incoherent Scatter Scientific Association) HF heating facility have conclusively demonstrated that the X-mode HF pump wave is also able to excite AFAI in the ionospheric F-region [5–7].

In this article, we present comparative results of AFAI features and behaviors induced by O- and X-mode high power HF radio waves (HF pump waves) by the bi-static scatter method using multichannel HF Doppler equipment, oblique sounding and CUTLUSS backscatter radar observations.

Experiment

The experiment was carried out on 18 February 2013 at evening hours in quiet magnetic conditions. The modification of the high latitude ionospheric F-region was produced by the HF heating facility (EISCAT/Heating) placed in Tromsø, Norway (69.58° N; 19.21° E) [8]. The high power O- or X-polarized HF radio wave was radiated in the field-aligned direction, or towards the magnetic zenith (the HF heater beam was tilted by 12° south of the vertical) at a frequency of $f_H = 4544$ kHz. HF pumping was done in the CW mode by cycles of 10 minutes “ON” and 5 minutes “OFF”. For radiation, phased array antenna number 2 was used with a pattern width of about 12–14° at — 3 dB level. The effective radiated power (ERP) was about 190 MW. In the course of the O-mode HF pumping, the heater frequency f_H was close to the critical frequency of the F2 layer f_{OF2} ($f_H \approx f_{OF2}$), while the X-mode pumping was done when $f_H > f_{OF2}$.

For remote sensing of HF-induced phenomena in the ionospheric F-region by the bistatic scatter method, multichannel HF Doppler equipment was used. It was installed at the AARI Gorkovskaya (GRK) Observatory near St. Petersburg, located at a distance of about 1,200 km away from the HF Heating facility at Tromsø. As diagnostic transmitters, the world HF AM broadcasting stations at Issoudun (France) and Vatican City, operated at frequencies of 15,180 kHz and 15,535 kHz respectively, were used. The AARI’s mobile multichannel HF Doppler equipment was also installed at the Roshydromet station at Lovosero (LOZ) in the Murmansk region (68.00° N; 35.02° E). The distance between the EISCAT/Heating facility and the LOZ station is 660 km [9].



Fig. 1. The geometry of the experiment on 18 February 2013 with the use of the EISCAT HF heating facility, the CUTLASS HF coherent radar, an oblique sounder on the Sweden — Tromsø — St. Petersburg radio path and AM HF broadcasting stations with receivers at GRK and LOZ stations

Рис. 1. Геометрия эксперимента 18 февраля 2013 г. с использованием нагревного стенда EISCAT, КВ радара CUTLASS, трассы наклонного ионозонда Швеция — Тромсё — Санкт-Петербург и КВ вещательных станций с приемниками на станциях «Горьковская» и «Ловозеро»

The CUTLASS (Collaborative UK Twin Located Auroral Sounding System) HF coherent radar [10], located at Hankasalmi, Finland (62.31° N; 26.61° E), was also utilized for AFAI diagnostics by the backscatter method. It is about 1,000 km to the south of the Tromsø EISCAT/heating facility. The CUTLASS radar runs in a stereo mode with range resolution of 15 km and temporal resolution of 3 s. Beam 5 was chosen with a narrow pattern of about 3.3° directed to the artificially disturbed region over Tromsø. The measurements were made simultaneously at frequencies of 9.9–10 MHz and 13.2–13.3 MHz. This allowed us to investigate AFAI behavior and features with a size across the geomagnetic field of $l_{\perp} \sim 15$ m and $l_{\perp} \sim 11,1$ m ($l_{\perp} = c/2f$, where f is the CUTLUSS radar operating frequency, c is the velocity of light). The choice and control of the heater frequencies were made in accordance with the Tromsø Ionosonde.

Apart from that, an automatic chirp ionospheric oblique sounder with linear frequency modulation (LFM) [11] ran on the Sweden — St. Petersburg radio path to receive the signals scattered from the AFAI. The LFM signals were received from Sweden (65.82° N; 21.70° E). The transmitter power was about 200 W. The reception point of the oblique sounder was located at the AARI Gorkovskaya Observatory. Oblique ionograms provide information concerning the regular propagation modes on the Sweden — St. Petersburg direct path. In the course of the experiment, signals scattered by the AFAI on the Sweden — Tromsø — St. Petersburg path were also observed on the ionograms.

Thus, in the course of the experiment on 18 February 2013, three different methods of AFAI diagnostics were utilized to provide different data sets related to the AFAI features and behaviors. The geometry of the experiment is shown in Fig. 1.

Results and discussion

The bi-static signals scattered from the AFAI (BSS) were recorded by multichannel HF Doppler equipment. On the dynamic Doppler spectra, they appeared as additional spectral components (scattered signals) shifted by a frequency to a positive or a negative range relative to the “zero” frequency, corresponding the HF signal carrier, which propagates along the great circle path (a direct signal). The additional spectral components appeared in the heater-on cycles and disappeared when the HF pumping was switched off. The value and the sign of the Doppler frequency shift is determined by the AFAI velocity vector in the artificially disturbed region.

Fig. 2 presents the dynamic Doppler spectra taken in the course of alternating O/X-mode HF pumping towards the magnetic zenith (MZ) at $f_H = 4544$ kHz on 18 February 2013. As seen in Fig. 2, the AFAI behavior differed during the O- and X-mode heating cycles. In the course of the O-mode HF pumping, the BSS were registered almost simultaneously with the heating facility turned-on and disappeared just after the heating was turned-off (see Fig. 2, left panel). By contrast, on X-mode cycles the AFAI growth time was about 1 min in the first cycle from the “cold” start and the decay reached a few minutes through the whole 5 min pause between the heater-on cycles (see Fig.2 right panel). In both cases, signals scattered by the AFAI with a size across the geomagnetic field of $l_{\perp} \sim 10$ m occurred.

Fig. 3 presents the CUTLUSS radar data received on the same day on 18 February 2013 from 14:30 to 18:00 UT with O- and X-mode HF pumping towards the magnetic zenith (MZ). It is important to emphasize that the size of the artificially perturbed region occupied by the AFAI was much larger when observed with O-heating than with X-heating. As seen from Fig. 3, under O-mode HF heating it reached an extension of 120–150 km (8–10 gates between 28–38 range gates), while the size of the perturbed region with X-mode the

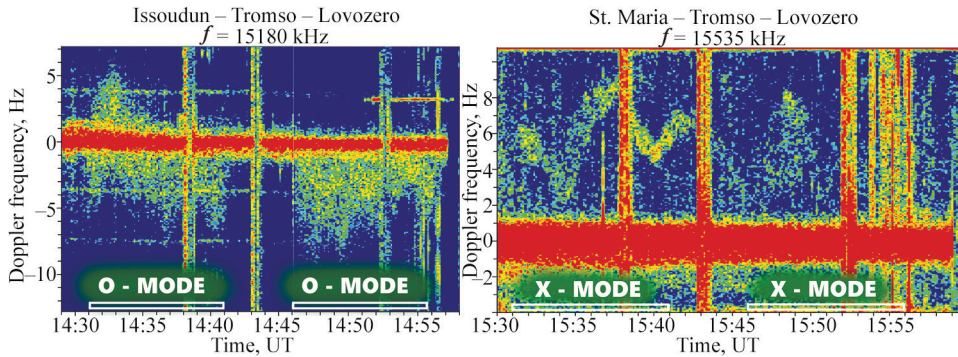


Fig. 2. BSS received on Issoudun — Tromsø — Lovozero and Vatican City — Tromsø — Lovozero radio paths during the alternative O/X-mode HF heating experiment on 18 February 2013. The HF pump wave radiated towards the magnetic zenith at frequency $f_H = 4544$ kHz by cycles 10 min on, 5 min off. The effective radiated power was ERP ~ 190 MW. The pump cycles and polarization are marked on the time axis

Рис. 2. Ракурсно-рассеянные сигналы на радиотрассах Исудён — Тромсё — Ловозеро и Ватикан — Тромсё — Ловозеро во время О/Х-нагрева 18 февраля 2013 г. Мощная КВ радиоволна излучалась в направлении магнитного зенита на частоте $f_H = 4544$ кГц циклами 10 минут нагрев и 5 минут пауза. Эффективная мощность излучения ERP ~ 190 МВт. Циклы нагрева и моды поляризации указаны на временных осях

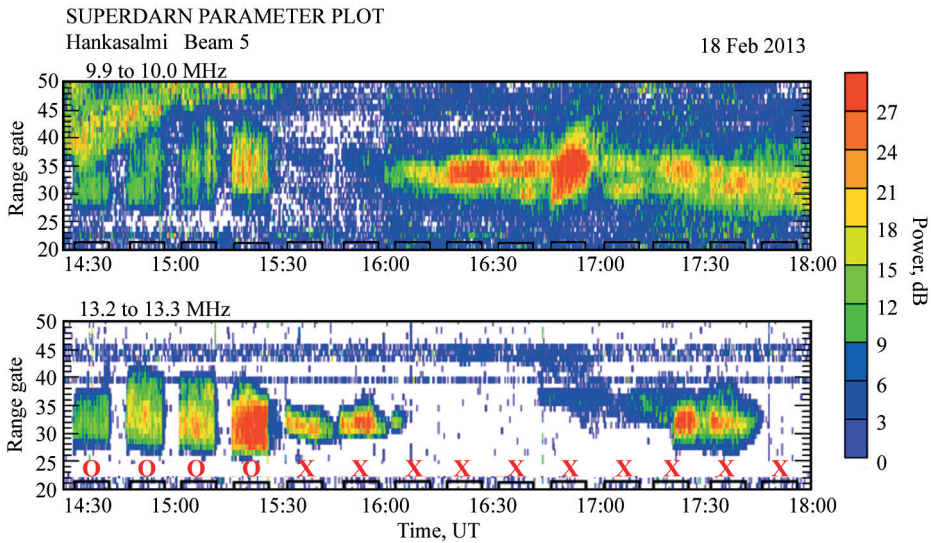


Fig. 3. CUTLASS radar data (beam 5) at frequencies of about 10 and 13 MHz during the alternative O/X-mode HF heating experiment on 18 February 2013. The HF pump wave radiated towards the magnetic zenith at frequency $f_H = 4544$ kHz by cycles 10 min on, 5 min off. The effective radiated power was ERP ~ 190 MW. The pump cycles and polarization are marked on the time axis

Рис. 3. Данные радара CUTLASS (луч 5) на частотах около 10 и 13 МГц во время О/Х-нагрева 18 февраля 2013 г. Мощная КВ радиоволна излучалась в направлении магнитного зенита на частоте $f_H = 4544$ кГц циклами 10 минут нагрев и 5 минут пауза. Эффективная мощность излучения ERP ~ 190 МВт. Циклы нагрева и моды поляризации указаны на временных осях

AFAI was only 60–105 km (4–7 gates between 28–35 range gates) from the CUTLASS measurements. The AFAI growth and decay times significantly differ for O- and X-mode HF pumping. The characteristic feature of the AFAI behavior upon X-mode heating is a large decay time that exceeds pauses between heater-on cycles (~5 min). Thus, the back scattered signals are continuously received, with the intensity increasing during the heater-on cycles.

The effects produced by the O- and X-mode HF pumping in the high-latitude ionospheric F-region, from the oblique ionograms on the Sweden — Tromsø — St. Petersburg radio path are demonstrated in Fig. 4. They are displayed as an additional track with the group delay time of scattered signals relatively to the regular propagation modes. This difference in the group delay time is caused by the different propagation lengths from the transmitter to the receiver for direct signals, propagating along the great circle path and signals scattered by the AFAI, generated above Tromsø, which propagated on the Sweden — Tromsø — St. Petersburg path. The duration of one oblique transmitting session was 2 minutes. Both oblique ionograms were recorded at the beginning of the turn-on cycles. The left ionogram was taken at the beginning of the O-mode heater-on cycle at 14:31 UT. The right ionogram was recorded at the beginning of the X-mode heater-on cycle at 16:46 UT. As seen in Fig. 4, BSS upon O-mode heating were registered in the frequency band between 10 and 15 MHz. It corresponds to the AFAI size across the geomagnetic field from $l_{\perp} \sim 10$ m to $l_{\perp} \sim 15$ m. Upon X-mode HF pumping the AFAI size was larger as compared with the O-mode heating. BSS were registered in the frequency band between 9 and 11.5 MHz, which corresponds to the size of the AFAI across the geomagnetic field from $l_{\perp} \sim 13$ m to $l_{\perp} \sim 17$ m. Despite the fact that the AFAI were generated both during O- and X-mode heating, the power of the X-mode AFAI observed at $f_H > f_{OF2}$ was ~ 6–9 dB

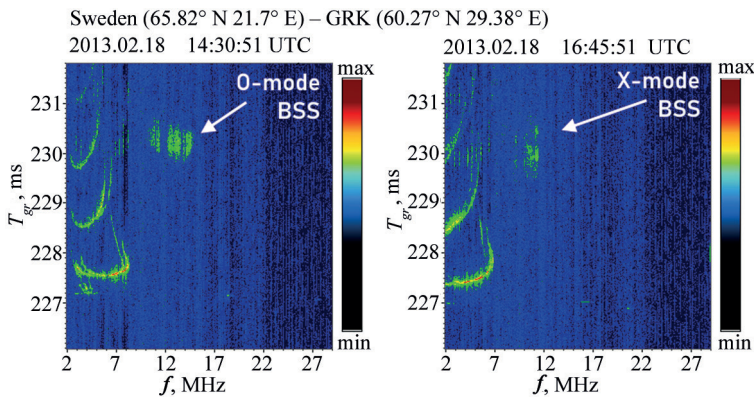


Fig. 4. The oblique ionograms with signals scattered from the AFAI on the Sweden — Tromsø — St. Petersburg radio path during the O- and X-mode HF pumping on 18 February 2013. The HF pump wave radiated towards the magnetic zenith at frequency $f_H = 4544$ kHz by cycles 10 min on, 5 min off. The effective radiated power was ERP ~190 MW. The BSS signals are marked with arrows

Рис. 4. Ионограммы наклонного зондирования ионосферы с сигналами, рассеянными от мелкомасштабных искусственных неоднородностей на радиотрассе Швеция — Тромсё — Санкт-Петербург во время О-/X-нагрева 18 февраля 2013 г. Мощная КВ радиоволна излучалась в направлении магнитного зенита на частоте $f_H = 4544$ кГц циклами 10 минут нагрев и 5 минут пауза. Эффективная мощность излучения ERP ~190 МВт. Ракурсно-рассеянные сигналы указаны стрелками

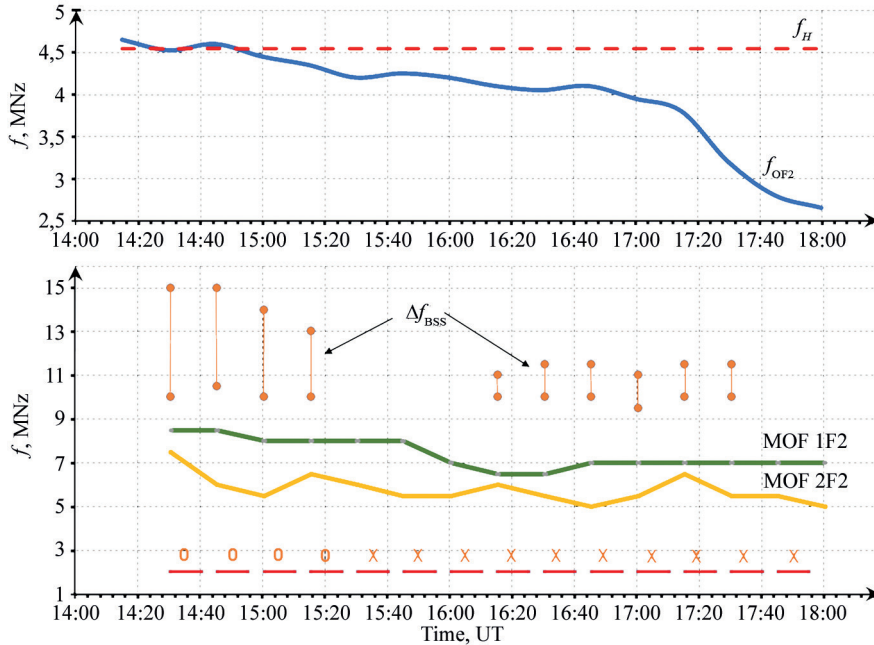


Fig. 5. The behavior in time of the critical frequency of the F2 layer (f_{OF2}), and the heater frequency f_H (top panel) and the maximum observable frequencies with one and two reflections from the F2 layer (modes MOF 1F2 and MOF 2F2) and the frequency band, in which the AFAI are generated (Δf_{BSS}) (bottom panel), in the course of the EISCAT Heating experiment on 18 February 2013

Рис. 5. Ход критических частот F2 слоя ионосферы (f_{OF2}) и частота нагревного комплекса f_H (верхний график), максимально наблюдаемые частоты однократного и двукратного отражения от F2 слоя ионосферы (моды MOF 1F2 и MOF 2F2) и частотный диапазон, в котором появлялись мелкомасштабные ионосферные искусственные неоднородности (Δf_{BSS}) (нижний график), в ходе нагревного эксперимента на стенде EISCAT 18 февраля 2013 г.

lower compared to the O-mode AFAI with the conditions of $f_H = f_{OF2}$. It is important to note that during the experiment the critical frequency of the F2-layer (f_{OF2}) dropped from 4.6 to about 2.5 MHz (see Fig. 5).

It was found that the X-mode AFAI are generated under quiet conditions (no precipitation of particles, longitudinal currents, or electrojet), when the HF pump is radiated towards MZ at frequencies that are both lower and much higher (up to 2 MHz) than the critical frequency of the F2 layer.

The features and physical driving mechanisms of AFAI are significantly different for O- and X-mode HF pumping, presenting challenges for understanding the relevant processes. It is well known that O-mode AFAI are excited at the pump frequencies of $f_H \leq f_{OF2}$ through the thermal (resonance) parametric instability [12, 13]. What is the origin of X-mode AFAI? The results from the EISCAT incoherent scatter radar (ISR) measurements have demonstrated that the emergence of strong Ne ducts with field-aligned electron density enhancements observed in a wide altitude range from 280–300 km up to about 600 km is a typical phenomenon for X-mode pulses [14]. In the course of O-mode pulses Ne enhancements did not usually occur. Note that Ne ducts induced by X-mode HF pumping were created at pump frequencies both below and above the f_{OF2} . Moreover, it was found

that the extent of the patch occupied by X-mode AFAI corresponded to the transverse size of the Ne duct [15]. The results obtained give grounds for believing that the Ne duct gives rise to X-mode AFAI. Strong horizontal gradients in the electron density exist on the boundaries of the Ne duct. The gradient drift instability can be excited on electron density gradients in the presence of the electric field of the X-mode HF pump wave, producing a wide spectrum of irregularities [16].

Summary

The paper presents results of research and comparison of AFAI features and behavior upon O- and X-mode HF heating in the high latitude F-region of the ionosphere using different diagnostic tools and methods. They include the following: the bi-static scatter method using HF multichannel Doppler equipment and an oblique sounder and the backscatter method of the coherent CUTLASS (SuperDARN) radar.

The joint use of various remote diagnostics tools provides a more comprehensive and complete study of the behavior and characteristics of the AFAI induced by the O- and X-mode HF pumping in the high-latitude F-region of the ionosphere, including the size of the artificially disturbed region occupied with the AFAI, the frequency band of BSS signals, the fine structure of BSS, the intensity, growth and decay times. It was shown that O- and X-mode AFAI have different characteristics and generation mechanisms.

It was found that X-mode AFAI are generated under quiet conditions, when the HF pump wave was radiated towards MZ at frequencies that are both below and above (up to 2 MHz) the critical frequency of the F2 layer. The results obtained give grounds for believing that the strong horizontal gradients in the electron density on the boundaries of the Ne duct in the presence of the electric field of the X-mode HF pump wave give rise to the excitation of gradient drift instability, producing a wide spectrum of irregularities.

Competing interests. No conflict of interest involved.

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Характеристики мелкомасштабных искусственных неоднородностей в высокоширотной F-области ионосферы по данным дистанционных методов наблюдений

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Расширенный реферат

Диагностика и прогноз явлений, происходящих в околоземном космическом пространстве и обусловленных солнечно-земными связями, становятся все более актуальной задачей, поскольку там функционируют автоматические космические аппараты, работают космонавты на пилотируемых космических станциях. Кроме того, ионосфера — среда, оказывающая влияние на распространение радиоволн, с чем связана работоспособность систем радиосвязи, навигации и телекоммуникаций.

Одним из методов изучения ионосферы является воздействие на нее мощным коротковолновым (КВ) радиоизлучением с помощью специальных наземных КВ радиопередатчиков большой мощности, так называемых КВ нагревных стенов. Мощные КВ радиоволны, взаимодействуя с ионосферой, ускоряют или «разогревают» электроны, выводя ионосферную плазму из состояния равновесия. Исследования возникающей при этом искусственно возмущенной локальной области ионосферы привлекают значительное внимание ученых возможностью изучения не до конца понятных на сегодняшний день физических особенностей вариаций параметров ионосферы по сравнению с их наблюдениями в естественных условиях. Взаимодействие мощной КВ радиоволны с ионосферой вызывает возникновение разнообразных нелинейных явлений в ионосфере, которые могут изучаться на контролируемой и повторяемой основе.

Одним из наиболее выдающихся явлений, обнаруженных в экспериментах по воздействию мощных КВ радиоволн на ионосферу, является генерация мелкомасштабных искусственных ионосферных неоднородностей (МИИН). МИИН вызывают ракурсное рассеяние коротковолновых и ультракоротковолновых (КВ и УКВ) сигналов, обеспечивая их распространение в диапазоне частот и на дальностях, недостижимых в естественной ионосфере. Таким образом, появляется возможность создания управляемых каналов радиосвязи. Для генерации МИИН, как правило, на всех КВ нагревных стендах мира используются мощные КВ радиоволны обыкновенной (О-мода) поляризации, которые эффективно взаимодействуют с ионосферной плазмой на высотах отражения и высотах верхнего гибридного резонанса. Радиоволны необыкновенной (Х-мода) поляризации отражаются ниже этих высот, поэтому не должны вызывать генерацию МИИН. Однако результаты наших недавних экспериментов на нагревном стенде EISCAT/Heating убедительно продемонстрировали, что генерация МИИН происходит и при Х-нагреве высокоширотной F-области ионосферы.

В данной работе представлены результаты сравнения характеристик МИИН при О- и Х-нагреве на основе использования метода ракурсного рассеяния диагностических КВ сигналов на МИИН с помощью станций наклонного зондирования ионосферы, когерентного КВ доплеровского радара CUTLASS (SuperDARN) и многоканального доплеровского комплекса «Спектр». Для модификации высокоширотной F-области ионосферы использовался нагревной стенд EISCAT/Heating, расположенный в г. Тромсё, Северная Норвегия. Результаты были получены в период эксперимента 18 февраля 2013 г. в вечерние часы при спокойных магнитных условиях. Мощная КВ радиоволна излучалась в направлении магнитного зенита на частоте 4,445 МГц. О-нагрев проводился на частотах вблизи f_{OF2} , а Х-нагрев при $f_H > f_{OF2}$. Показано, что совместное использование различных средств дистанционной диагностики МИИН позволило получить новые данные о характеристиках МИИН при О- и Х-нагреве, включая размер искусственно

возмущенной области ионосферы, занятой МИИН, диапазон частот, в котором наблюдаются ракурсно-рассеянные сигналы РРС, и их тонкую структуру, интенсивности, времена нарастания и релаксации МИИН в высокоширотной F-области ионосферы. Показано, что МИИН при O- и X-нагреве имеют различные характеристики и механизмы генерации. Характерной особенностью МИИН при X-нагреве, является возможность их генерации не только на частотах ниже критической частоты слоя F2 ($f_H \leq f_{OF2}$), как это происходит при O-нагреве, но и на частотах существенно выше (до 2 МГц) критической частоты F2 ($f_H > f_{OF2}$). Результаты выполненных исследований дают основания полагать, что сильные горизонтальные градиенты электронной концентрации при наличии электрического поля мощной X-волны, перпендикулярного магнитному полю, приводят к генерации градиентно-дрейфовой неустойчивости, ответственной за возбуждение МИИН.

Ключевые слова: высокоширотная ионосфера, дистанционная диагностика, мелкомасштабные искусственные ионосферные неоднородности, мощная КВ радиоволна, нагревной стенд, ракурсное рассеяние

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